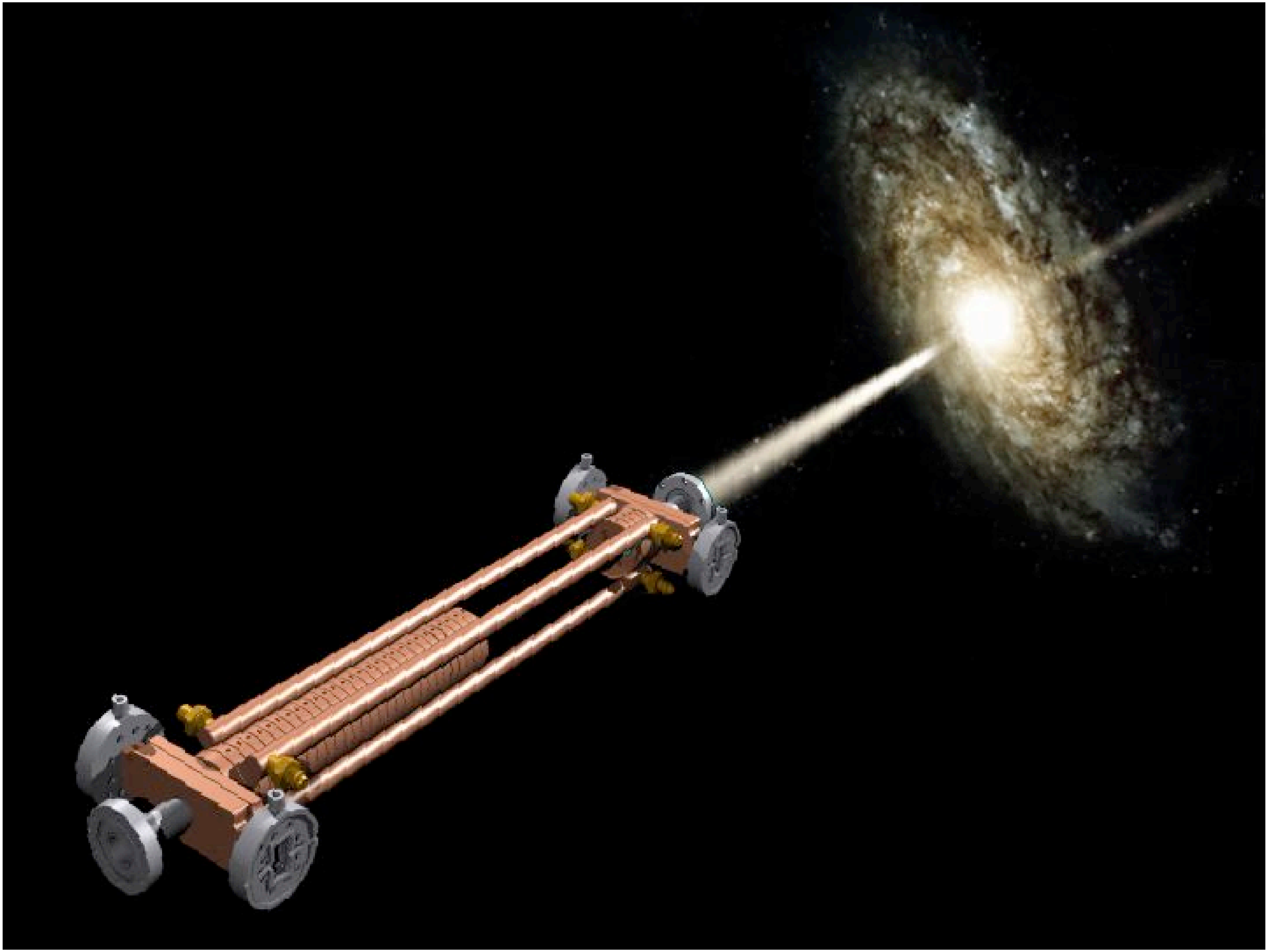
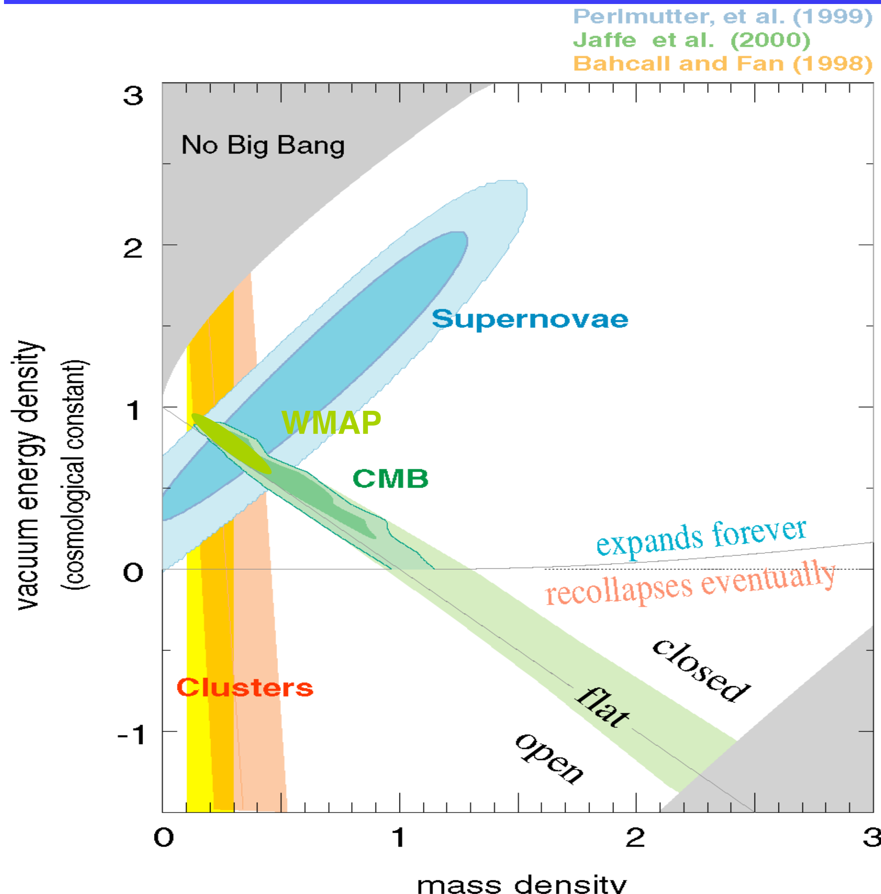
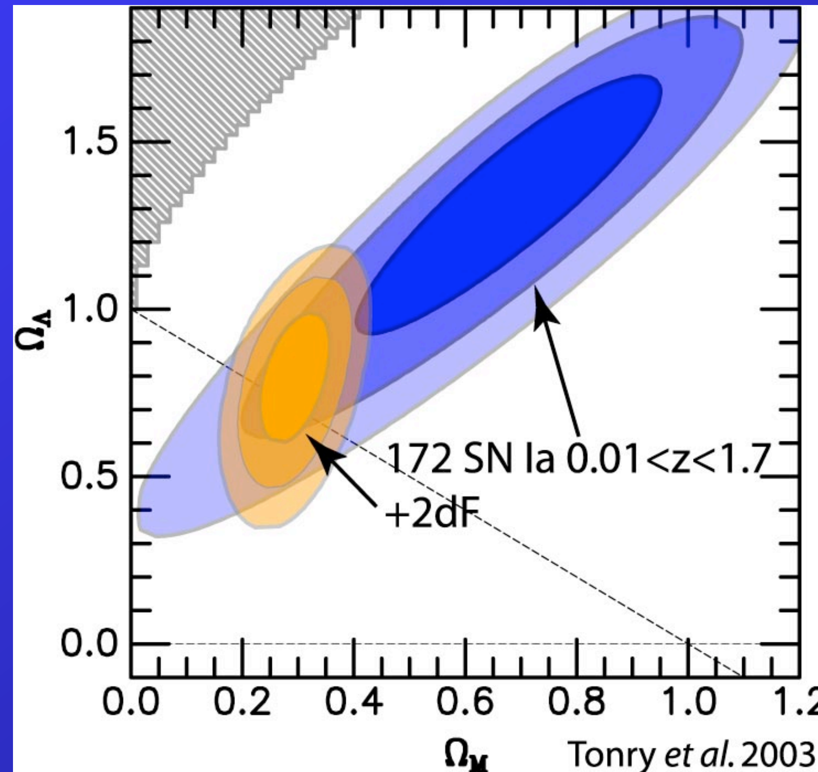


Outline

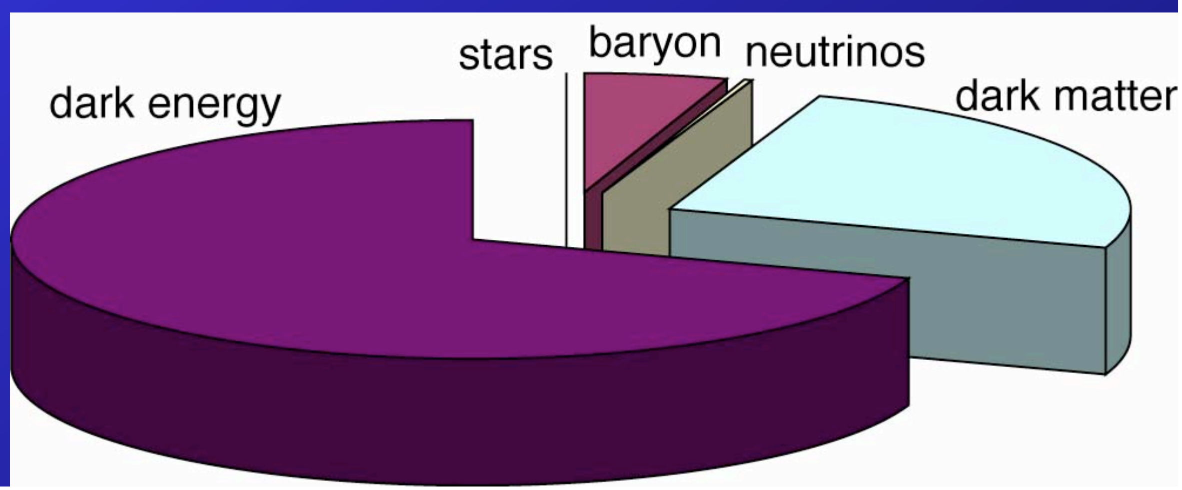
- The Big Unknowns in Modern Cosmology
- Dark Matter
- Baryogenesis
- Cosmic Rays (brief)
- Dark Energy and Inflation (!)
- The ALCPG Working Group on Cosmological Connections

The New Paradigm





- Strange new universe
- Ω_{baryon}~ 0.05
- Ω_{matter}~ 0.30
- Ω_{Λ}~ 0.65



We know what these particles are but not why they haven't met their antiparticles

We don't know what these particles are but we have some well-motivated ideas

We have absolutely no idea what this stuff is and we have no ideas that are well-motivated and well-developed!

Topics of Primary Interest

- Issues raised enhance and sharpen the search for the Higgs boson, supersymmetry, extra dimensions…
- Need particle physics and cosmology to find the answers.
- Explore what a Linear Collider will bring to this enterprise.

Focus on four potential areas of connections between linear collider physics and cosmology

- Dark matter
- Baryogenesis
- Cosmic rays
- Inflation and dark energy

↓ Decreasing direct connection

Briefly discuss each of these soon

Dark Matter

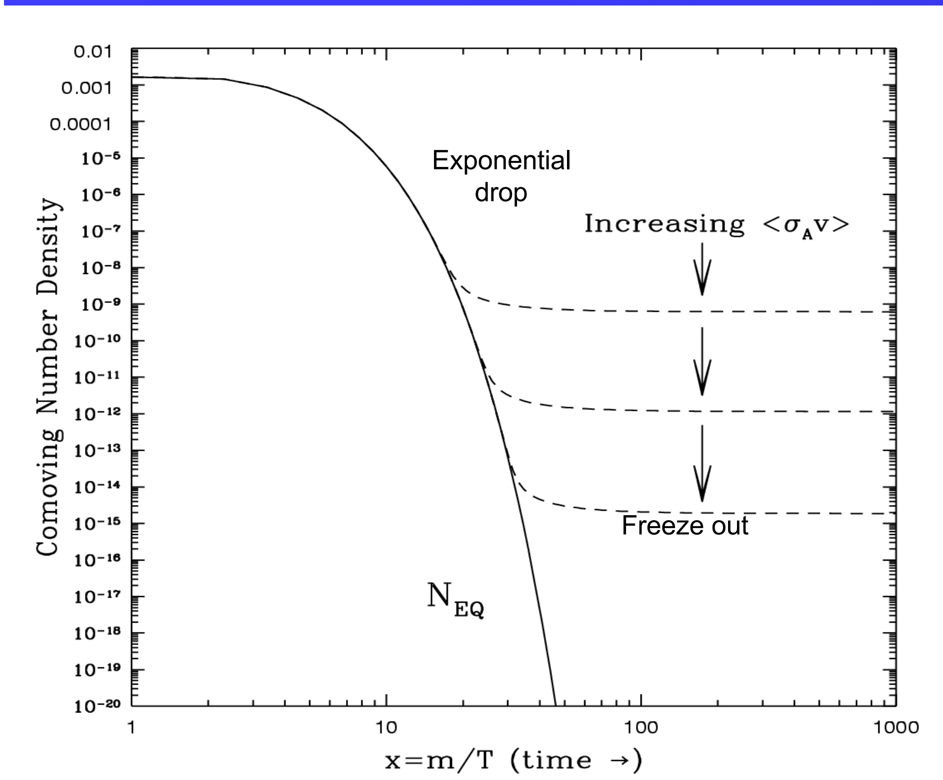
A prime dark matter candidate is the WIMP
→ a new stable particle χ.
Number density *n* determined by

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Dilution from expansion — $\chi \bar{\chi} \rightarrow f \bar{f}$ — $f \bar{f} \rightarrow \chi \bar{\chi}$

- Initially, $\langle \sigma v \rangle$ term dominates, so $n \approx n_{eq}$.
- Eventually, *n* becomes so small that the dilution term dominates and the co-moving number density is fixed (*freeze out*).

Abundance of WIMPs



Universe cools, leaves residue of dark matter with

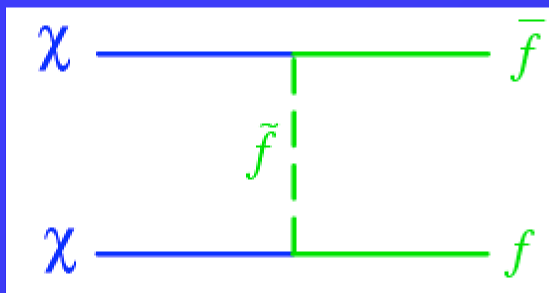
$\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$

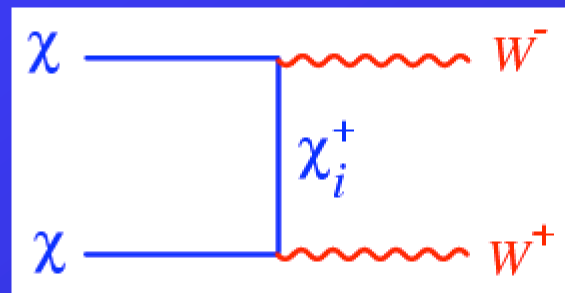
- Weakly-interacting particles w/ weak-scale masses give observed Ω_{DM}
- Strong, fundamental, and independent motivation for new physics at weak scale

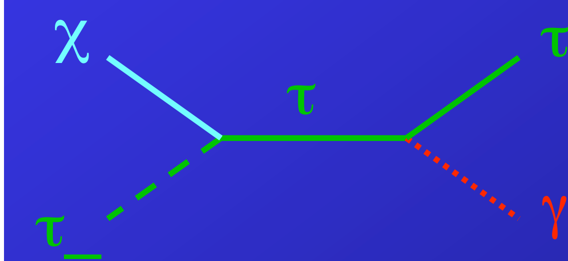
- Could use the LC as a ***dark matter laboratory***
- Discover WIMPs and determine their properties
- Consistency between properties (particle physics) and abundance (cosmology) may lead to understanding of Universe at T = 10 GeV, t = 10^{-8} s.

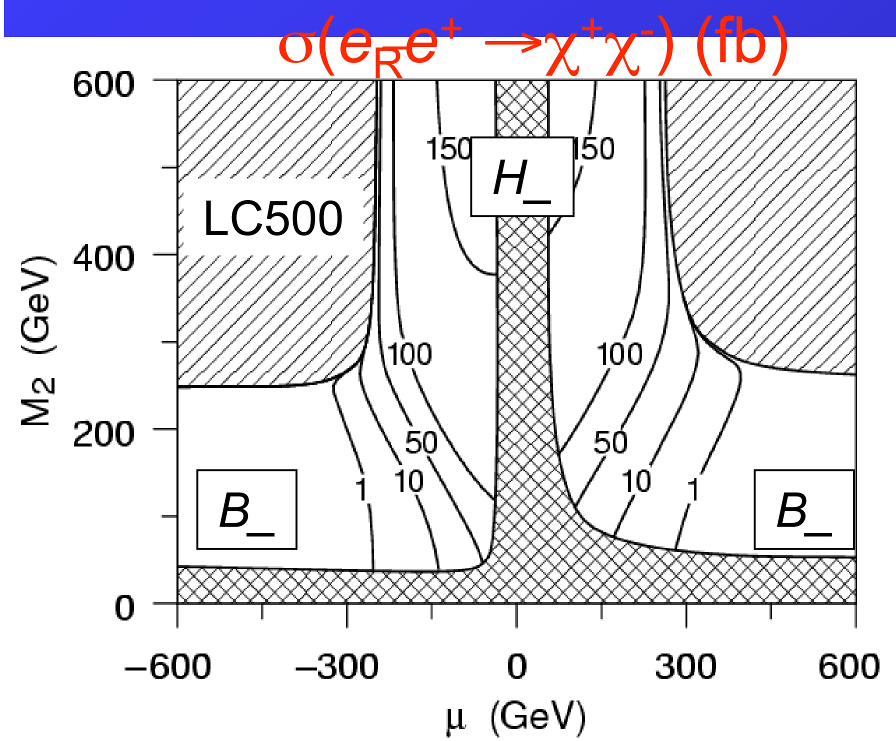
An Example: Neutralinos

- In more detail: χ annihilation sensitive to *many* processes.









Feng, Murayama, Peskin, Tata (1995)

- Requires precise knowledge of χ mass and Sfermion masses (from kinematics)
- *Also* χ gaugino-ness (through polarized cross sections)
- and Δm to ~ few GeV

Model-independent determination of Ω_c to a few % challenging but possible at LHC/LC.

Important Questions

- Axions and superheavy candidates will escape the LC.
- But can the LC carry out this program for all thermal relics (and distinguish the various possibilities)
  - Neutralino dark matter
  - Kaluza-Klein dark matter
  - Scalar dark matter
  - SuperWIMP dark matter
  - Branon dark matter
  - …
- This will require a detailed and specific program of analysis

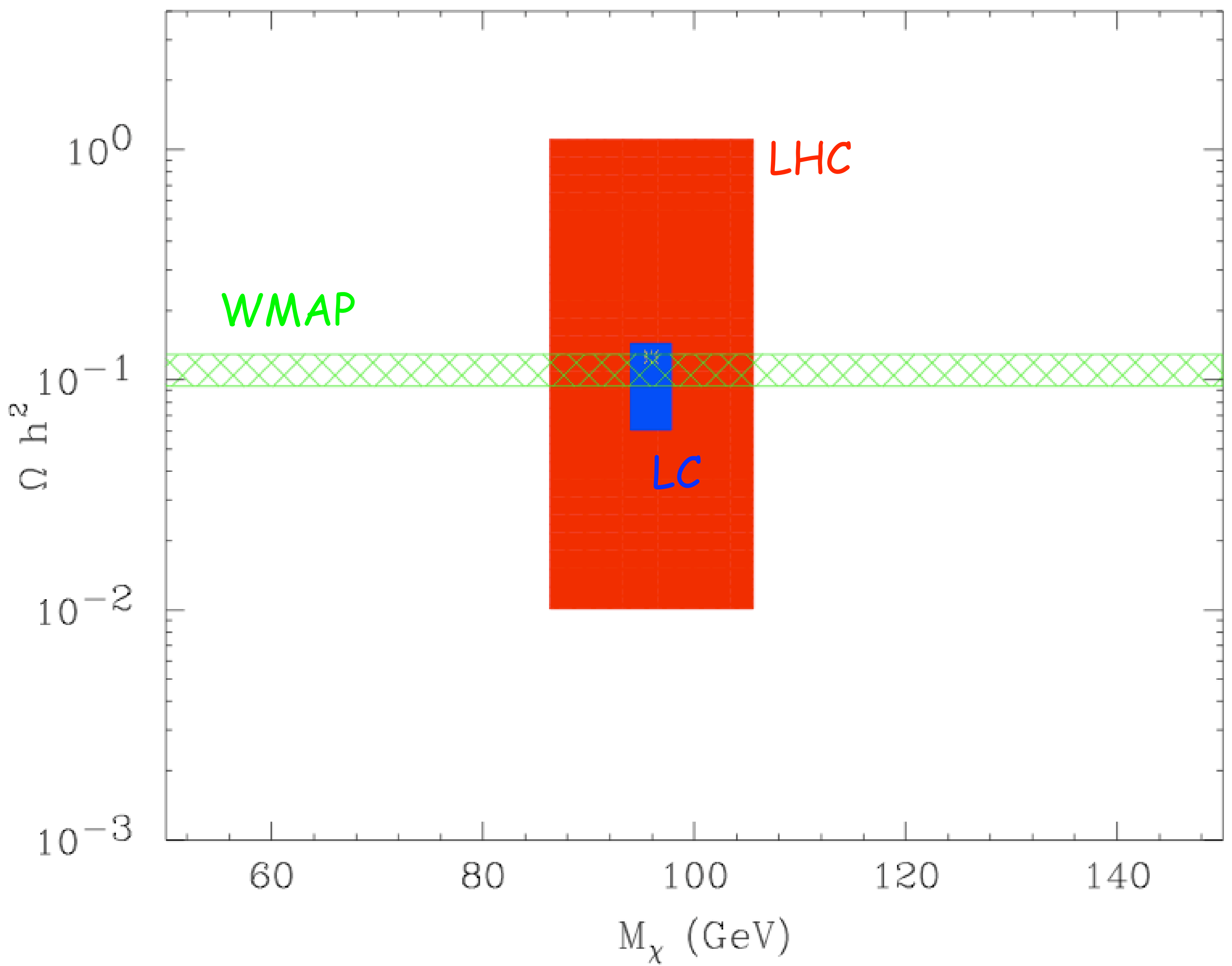
What Might the LC Buy Us?

Simple example (courtesy of Andreas Birkedal)

- Suppose important point in SUSY parameter space is one at which not all masses important
- Only need to measure a few masses to get the relic density

Concrete example - point B′ of "updated benchmark" points:
mSUGRA w/ $\tan\beta$ = 10, sgn(μ)=+1, m_0=57, $m_{1/2}$=250, A_0=0

- Dark matter candidate is the neutralino
- Half the neutralinos and charginos are below 200 GeV
- All of the sleptons are below 200 GeV
- All of the squarks are below 600 GeV
- Heaviest particle - gluino - 611 GeV



LHC
WMAP
LC
10^0
10^{-1}
10^{-2}
10^{-3}
Ωh^2
60
80
100
120
140
M_χ (GeV)

Baryogenesis

BBN and CMB have determined the cosmic baryon content:

$$\Omega_B h^2 = 0.024 \pm 0.001$$

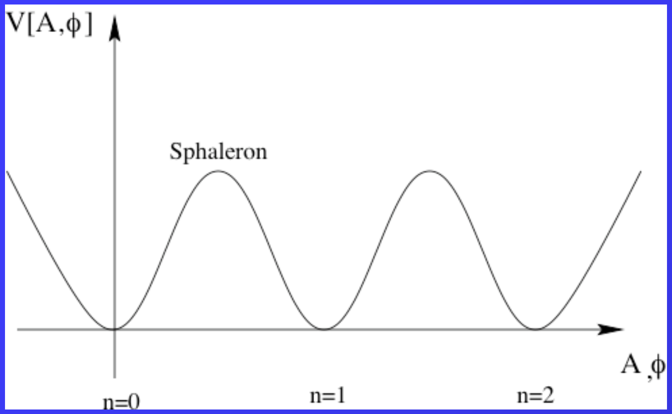
To achieve this a particle theory requires (Sakharov, 1968) :

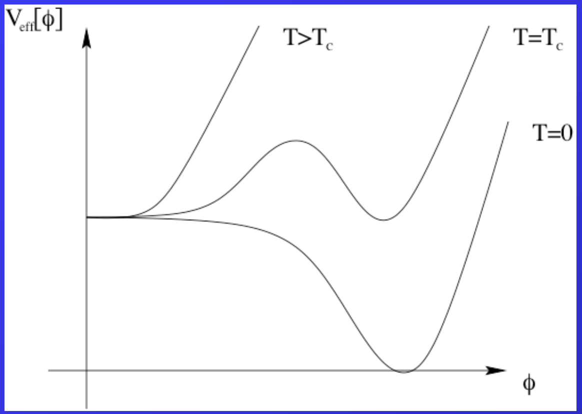
- Violate Baryon number (B) symmetry
- Violate the Charge conjugation and Charge-Parity symmetries (C & CP)
- Depart from thermal equilibrium
- There are LOTS of ways to do this!

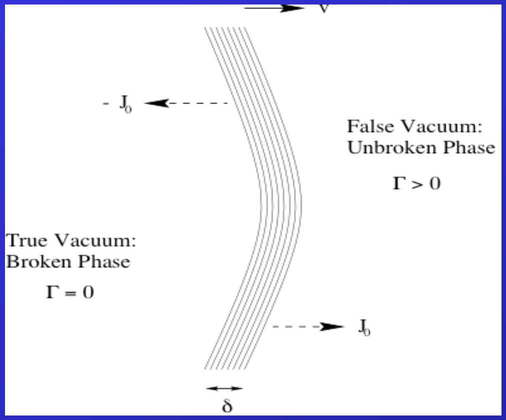
An Important Clue for Particle Physics

- Many scenarios for baryogenesis rely on physics at the GUT scale. In these cases the LC will have little to add.
- However, an attractive and testable possibility is that the asymmetry is generated at the weak scale.
- The Standard Model of particle physics, even though in principle it satisfies all 3 Sakharov criteria, (anomaly, CKM matrix, finite-temperature phase transition) cannot be sufficient to explain the baryon asymmetry!
- This is a clear indication, from observations of the universe, of physics beyond the standard model!

Electroweak Baryogenesis





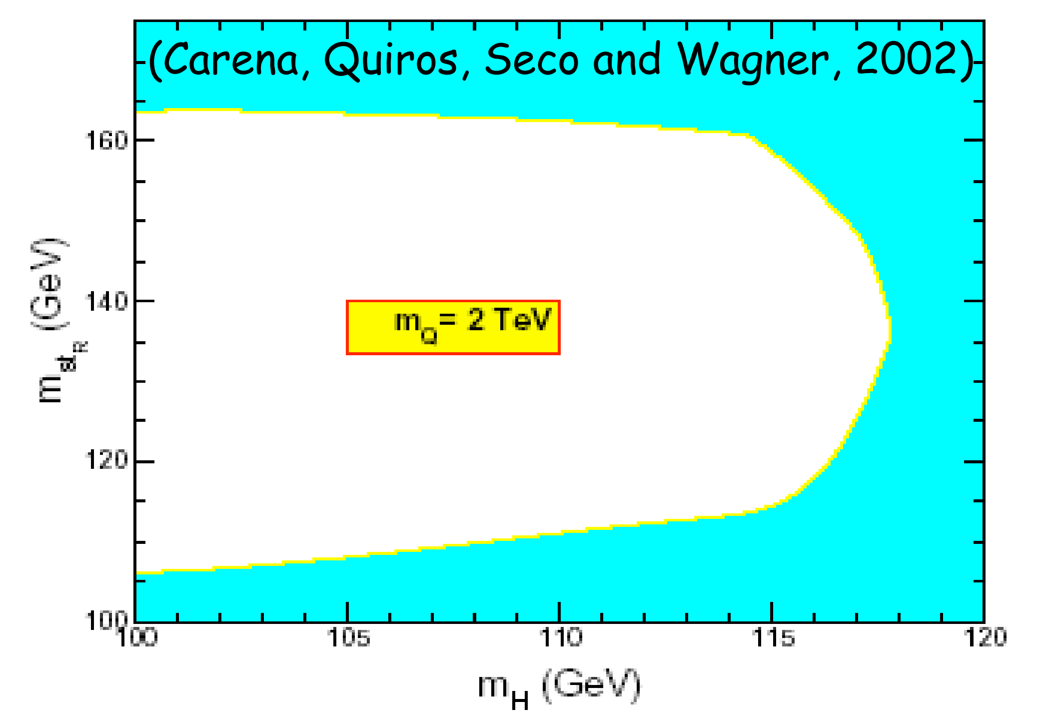


- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe

Physics involved is all testable in principle at colliders.
Small extensions needed can all be found in SUSY,
Testability of electroweak scenarios leads to tight constraints

Bounds and Tests

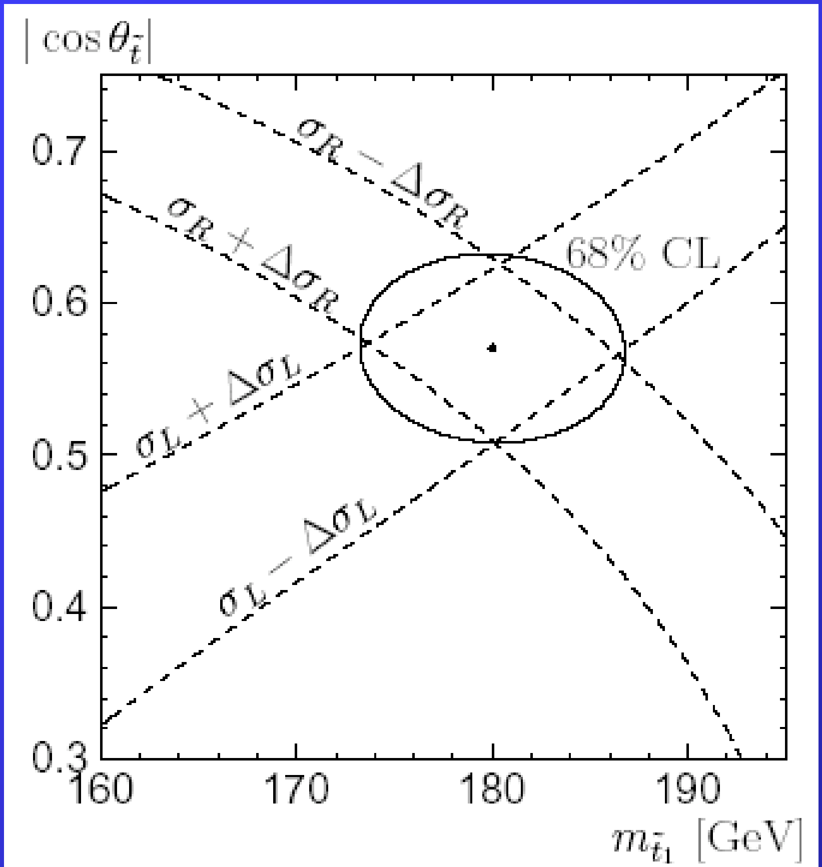
- In supersymmetry, sufficient asymmetry is generated for *light Higgs, light top squark, large CP phases*
- Promising for LC!
- Severe upper bound on lightest Higgs boson mass, m_h <120 GeV (in the MSSM)
- Stop mass may be close to experimental bound and must be < top quark mass.



Very nice description of bounds in Dan Chung's parallel talk at the SLAC linear collider meeting (Linked from ALCPG cosmology subgroup page - more later!)

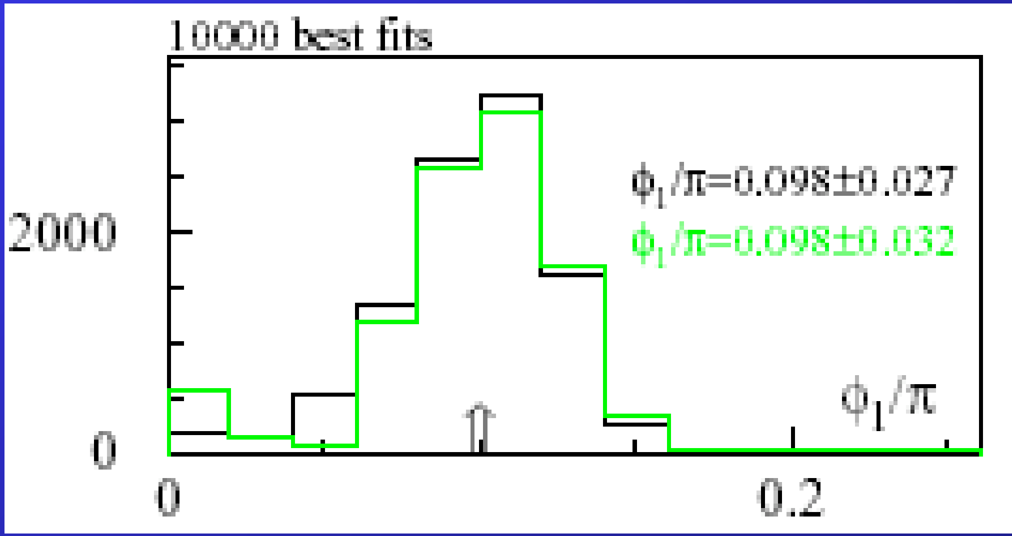
Baryogenesis Parameters at the LC

Top squark parameter constraints for 10 fb^{-1} using $e^-_{R,L}e^+ \rightarrow$ stop pairs



Bartl et al. (1997)

CP phase constraints using chargino/neutralino masses and cross sections



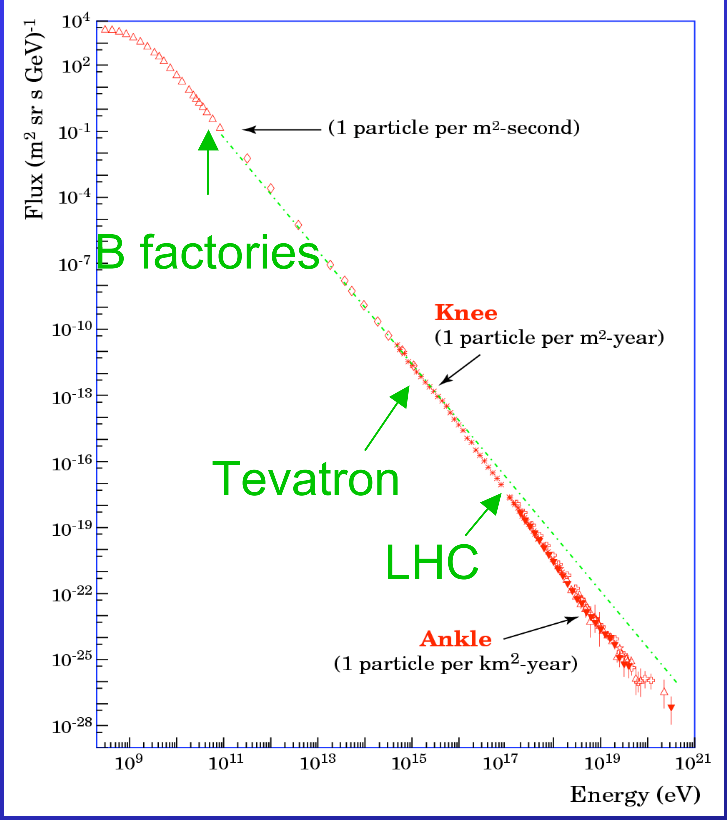
Barger et al. (2001)

Other Connections

- Another important test for EWBG may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector
- Important to remember that BG may be due to different and entirely new TeV scale physics (e.g. Langacker et al. Z' model)
- May learn indirectly about leptogenesis (Peskin et al.)
- How well can we determine Ω_B in these scenarios?
- Does the LC have anything to say about GUT-scale baryogenesis/leptogenesis?

Cosmic Rays

- Observed with energies ~10^{19} eV $\Rightarrow E_{CM}$~100 TeV in collisions.
- E_{CM} > any man-made collider.
- Cosmic rays are already exploring energies above the weak scale!



Drawbacks:

- Miniscule luminosities.
- Event reconstruction sparse and indirect.

Colliders may help interpret upcoming ultrahigh energy data.

The GZK Paradox

- Protons with ~10^{20} eV energies quickly lose energy through

$$p\,\gamma_{CMB} \rightarrow n\,\mathrm{p}^{+}$$

so probably must be emitted from nearby, but no local sources found.

- Solutions:
  - Bottom-up: e.g., CRs are gluino-hadrons.
  - Top-down: CRs result from topological defect decays, should produce up-going cosmic neutralinos if SUSY exists.

Testable predictions for colliders.

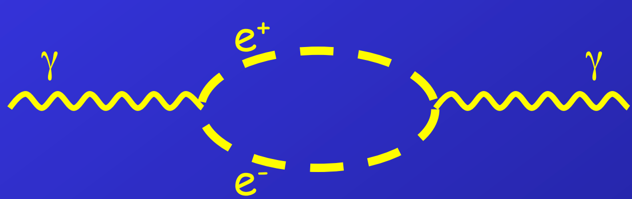
Inflation and Dark Energy

- We know essentially nothing about dark energy
- Tied to our ignorance about the cosmological constant.
- Exploration of Higgs boson(s) and potential may give insights into scalar particles, vacuum energy.

- Vacuum is full of virtual particles carrying energy.
- Should lead to a constant vacuum energy. How big? - ∞

BUT…

- While calculating branching ratios - easy to forget SUSY is a *space*-time symmetry.
- A SUSY state $|\psi\rangle$ obeys Q $|\psi\rangle$=0, so H $|\psi\rangle \propto \{Q,Q\}$ $|\psi\rangle$=0
- Only vacuum energy comes from SUSY breaking!



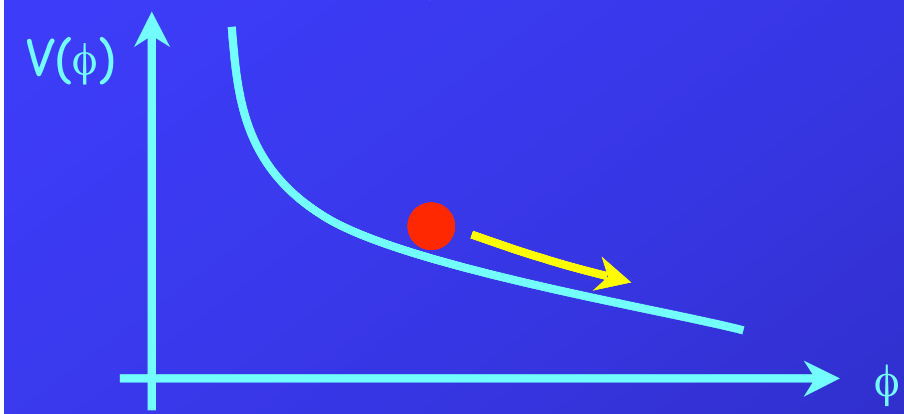
$$\rho_\Lambda \sim M_{SUSY}^4$$

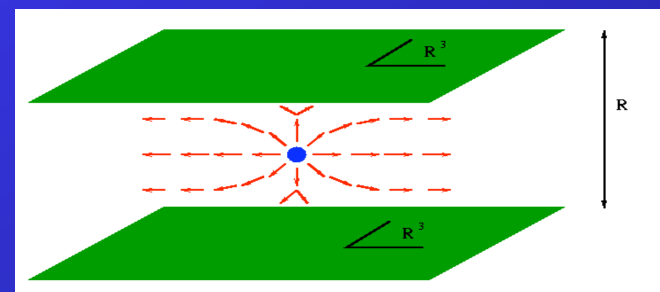
Still 10^{60} too big!

Other Possibilities

Inflation and dark energy may be due to fundamental scalars or extra-dimensional dynamics:

Use scalar fields to source Einstein's equation.





Gravity in the bulk, SM fields only on the (visible) brane.

- Possible LC will provide much-needed insight into these
- The LC can probe details of the Higgs potential - don't expect it to be the inflaton, but would be our first prototype of a scalar potential.
- Dvali-Kachru new-old inflation idea requires new field at TeV scale to generate perturbations - specific LC signatures …

The ALCPG Working Group on Cosmological Connections

http://www.physics.syr.edu/~trodden/lc-cosmology/

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- Michael Peskin (SLAC)
- Mark Trodden (Syracuse, co-Chair) trodden@physics.syr.edu

Our charge from Jim Brau and Mark Oreglia

- Form working group in ALCPG framework
- Determine and prioritize topics with potential connections
- Produce white paper by Fall 2004

A Cautionary Comment

I am not a conservative! (and neither are most of you)

- It is important to have a common framework - so it *is* useful to think about mSUGRA in this context
- However, should recognize this is a ridiculous constraint on possibilities, even within SUSY
- Shouldn't fool ourselves that we are covering "a large part of parameter space" - more work is needed - don't give up!

- On topic of not giving up - despite fairly solid theoretical arguments, too early to say we won't learn about dark energy from terrestrial physics - we know nothing about this!
- Would be nice to see a proof-of-principle model.

Final Comments

- Science: A linear collider may help address some of the biggest and most pressing issues in cosmology - dark matter, baryogenesis, cosmic rays and perhaps even give hints about dark energy and inflation.
- Science: A strong collider program is a necessary and natural complement to cosmological observations if we are to unravel the fundamental physics reasons behind the universe we observe.
- PR: This is important because people can see stars and galaxies, and feel that the universe is much more tangible than, say, the Higgs boson or supersymmetry - as beautiful as they may be to most of us.

-Thank You -